Analysis of Low-carbon Power Infrastructure: A Case Study of Taiwan

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Abstract

If it is assumed that CCS (Carbon Capture and Storage) technologies are successfully applied to fossil-fueled power plants before 2025, through scenarios analyses, this study found that the option of CCS could sufficiently meet both power supply demands and GHG emissions standards, under the circumstances of non-nuclear power and minor renewables. These results inferred that CCS is the most feasible way for Taiwan to construct a low-carbon power infrastructure, because the all installed capacities are very close to those of BAU (Business As Usual). However, the CCS option is not the most economical one, due to the significant increase of generation cost up to 34%. Besides, the commercialization of CCS in the short term is still a question. Inherently, Taiwan lacks fossil energies but reserves abundant renewables. Although renewable energy is not the mainstream of power generation currently, it is believed that its shortcomings (e.g., unsTABLE supply and high price) could be overcome eventually, if the substantial progress of technology is involved. In the viewpoint of national security, the development of renewables is an indispensable policy for Taiwan.

Keywords

Power Infrastructure; Low-carbon Emissions; Scenarios Analyses; Least-costing Analysis; Taiwan

Foreword

Currently, Taiwan's energy structure is facing two kinds of crises, as described in the following:

- Complete dependence on energy supply—Taiwan imports more than 99% of energy demand from foreign countries, and mostly from the politically unstable countries in the Middle East. This is really the biggest concern in the national energy security policy. For example, in 2010, Taiwan imported 144.5 million kilo-liters oil equivalent (KLOE) of energy by spending 1.5943 trillion NTD, which was equivalent to 11.74% of GDP in that year (BOEMOEA, 2010a).
- Serious greenhouse gas (GHG) emissions—in 2009, the GHG emissions of Taiwan was 10.9 ton-CO2e/person, approximately 2.5 times that of the world (4.3 ton-CO2e/person), world ranking to No. 17. The main cause is the excessive use of fossil energy. From a global point of view, the carbon dioxide emitted from the burning of fossil fuels creates the greenhouse effect on the atmosphere and in turn changes the global climate.

Based on the above reasons, the development of clean energy—in particular renewables—is regarded as the national top priority. As shown in TABLE 1, according to the referential literature (Chen et al., 2010), Taiwan has abundant renewable energy sources, of which the total reserves are estimated about 78.02 kWh/person-day, approximately 2.65 times currently national power supply (29.43 kWh/person-day) (BOEMOEA, 2010a). Moreover, since the nuclear disaster occurred in Japan on March 11, 2011, many countries in the world have adopted the development of non-nuclear energy sources as their major energy policies. Therefore, the deployment of renewable energy in large scale has become a main course for Taiwan in the way of a sustainable development.

In the viewpoints of engineering and technology, since the GHG emissions of nuclear power generation are close to zero, and the energy density of nuclear fuel is extremely large but with the merits of easy storage, nuclear power may be regarded as a clean energy. At the same time, the availability and stability of nuclearpower generation are high, besides nuclear power can be used as a base load power, which is not the advantage of renewable energy power generation. Secondly, according to the BP statistics (BP, 2011), in 2010, the global known reserves of natural gas and coal were respectively 59 years and 118 years for the future use. Although with high GHG emissions, the fossil-fueled power generation is often used as a base

TABLE 1 STATISTICS OF THE POWER POTENTIAL OF RENEWABLE ENERGY RESERVES IN TAIWAN (in kWh/person-day)

	Solar	Wind	Biomass	Marine	Geothermal	Hydro	Total
Reserves	24.27	29.90	1.82	4.57	0.67	16.79	78.02
Proportion	31.3 %	38.3 %	2.3 %	5.8 %	0.8 %	21.5 %	100%

load power. With rich reserves of coal and natural gas in the world, in recent years, many countries are devoted to the research and development of clean coal and CCS technologies. Given the above reasons, in the international levels, the nuclear energy has often been regarded as one low-carbon power generation option, while the CCS fossil-fueled power generation is also attached with a high expectation for the future.

Emissions-abating Targets of the World and Taiwan

Climate change caused by global warming is by far the most important issue. Formed by the excessive GHG emissions, the greenhouse effect has been recognized as the main cause of global warming. Therefore, many governments in the world regard GHG emissions abatement as a top priority in terms of national energy policy, including Taiwanese Government and the UN's IPCC (Intergovernmental Panel on Climate Change), whereby all kinds of GHG emissions standards have been formulated.

Carbon Emissions Etatus and IPCC Emissions Ebatement Plan B1

The results of a study concerning the years 2000-2006 indicated that the global annual carbon emissions due to human activities were 9.1 billion tons (equivalent to 33.4 billion tons of carbon dioxide), of which emissions from the combustion of fossil fuels were responsible for 7.6 billion tons; while the remaining 1.5 billion tons were emitted as a result of changes in land-use. During the same period, for the carbon emitted into the atmosphere, 2.8 billion tons was absorbed annually by vegetation and soil; 2.2 billion tons entered the ocean; and the other 4.1 billion tons remained in the atmosphere. Accordingly, in recent years, around 45% of carbon dioxide emissions caused by human activities could not be absorbed by the oceans, soil or vegetation, and this proportion is still increasing. The greenhouse effect has been mostly responsible for a marked worsening of global weather (Canadell et al., 2007).

Within the 1,000 years before the year 1750, when the industrial revolution began, the concentration of carbon dioxide in the atmosphere had remained steady at 280ppm. However, the concentration of carbon dioxide slowly increased after 1750, rising to 381ppm in 2006; and the rate of increase between 2000 and 2006 was 1.93ppm/yr (Canadell et al., 2007). The concentration in 2006 was not only the highest in 650,000 years (Siegenthaler et al., 2005), but also may be the highest in the past 20 million years (Pearson et al., 2000). According to the latest observations made by the National Atmospheric and Oceanic Administration of United States, the concentration of carbon dioxide in the atmosphere reached 388ppm in 2010.

In 2010, the total emissions of GHGs globally reached about 47 billion tons of carbon dioxide equivalents (CO2e). Based on various possible scenarios of economic development and population growth globally over the next few decades, IPCC has generated various estimates on carbon emissions. One of the most optimistic emission scenarios (B1) for 2030 involves global total emissions of 54 billion tons of carbon dioxide equivalents (CO2e), falling to 23 billion tons in 2100 (Metz et al., 2007).

When this B1 emission scenario was simulated using 19 meteorological models, the Earth's surface temperature in the year 2100 was found to rise by 1.4~2.9 degrees Celsius from that in 1980 to 2000 (Vermeer et al., 2009). The World Climate Conference held in Copenhagen at the end of 2009 designated "2oC" as the target cap on global warming, with a view to mitigating the impact of global warming on human survival. The B1 scenario requires 40 billion tons of global carbon emissions in 2030 (Metz et al., 2007). Since the global population is estimated to be 8 billion people in 2030 (UN, 2004), the global carbon dioxide emissions must be limited to 5 tons/person. The B1 scenario will maintain a carbon dioxide concentration of 550ppm in the atmosphere.

Emission-abating Target of Taiwan in Response to Global Warming

In 2010, the carbon dioxide emissions in Taiwan were 11 tons per capita (BOEMOEA, 2011). To meet the IPCC's 2030 target—5 tons per capita, Taiwan must reduce its emissions by 54.5% between 2010 and 2030.

In 2008, Taiwanese Government released "Sustainable Energy Policy Guidelines" which proposed that a sustainable energy policy should have three foundations: the efficient use of limited resources, the development of environmentally friendly clean energy, and the ensuring of a sTABLE energy supply. With respect to the development of clean energy, an emissions standard was formulated: the national carbon dioxide emissions in 2025 should return to the level in 2000.

Based on this standard, the carbon dioxide emissions of Taiwan must be reduced to 9.7 tons per capita in 2025. This reduction is equivalent to an abating rate of 11.8% between 2010 and 2025. Obviously, this emissions standard is much looser than that of “B1 scenario” proposed by IPCC for 2030. Therefore, this study set 2025 and 2030 as the two target years respectively corresponding to the two GHG emissions-abating standards set by "Sustainable Energy Policy Guidelines" and "IPCC’s B1 Emissions Scenario". Meanwhile, "power generation" is the largest source of GHG emissions in Taiwan. Under the constraint of minimal power generation cost, this study would analyze Taiwan’s low-carbon power infrastructure to satisfy the power supply demand in the future in terms of both amounts of "power generation" and "reserve capacity ratio".

Targets of Power Generation and GHG Emissions in the Energy Sector

According to the forecast made by BOEMOEA (Bureau of Energy, Ministry of Economic Affairs) in 2011, the average annual growth rate of power supply of Taiwan is 2.8% between 2010 and 2029. The power supply needed for the year 2029 would be 276.26 billion kilowatt-hours (BOEMOEA, 2010b). Suppose that the average annual growth rate remains unchanged, the power needed for the year 2030 will hit 386.79 billion kilowatt-hours.

The above power supply forecast can be called a "BAU (Business As Usual)" case, which was planned by considering eight factors in Taiwan, namely, economic growth, industrial structure, population growth rate, temperature, electric price, demand side management, large developing/planning cases, and fuel price of power generation (BOEMOEA, 2010b). In addition, other aggressively incentive programs of energy conservation and carbon reduction are also considered in the current energy policy of Taiwan: such as, the promotion of energy efficiency, the formulation of national renewables development targets, and the extensive use of gas-fired power generation.

In 2025, the total power supply demand based upon national expectations will reach 349.64 kilowatt-hours (MOEMOEA, 2010b)—divided by the estimated population of 23.4 million people (CEPD, 2010) and 365 days in one year—which turns out to be 40.9 kWh/person-day. Similarly, the total power supply demand for 2030 would be 45.5 kWh/person-day.

Here, "power supply" was defined as "power generation" deducted by the power used by the power plant itself. If the data of BOEMOEA (2010a) is adopted, the percentage of power generation used by the power plant itself was 8.09%. Therefore, the minimal values of “total power generation” targeted for 2025 and 2030 Taiwan would be respectively 44.5 kWh/person-day and 49.5 kWh/person-day.

According to the statistics of BOEMOEA in 2011, the GHG emissions share of power sector was 65.7% by taking the all sectors as a whole. Assuming that this percentage remains unchanged till 2030, in BAU scenario, the remaining 34.3% would come from miscellaneous emissions items besides power generation.

As mentioned earlier, 5.0 ton-CO_{2e}/person is the emissions-abating target set for Taiwan for the year 2030, so relative to the 11 ton-CO_{2e}/person of 2010, the national carbon dioxide emissions-abating scale would be 54.5%. This study reasonably assumed that the miscellaneous sector would reduce the carbon emissions with the same scale of 54.5%, then the power sector would at least reduce its annual carbon dioxide emissions to 3.28 tons ($=5.0-(11.0\times34.3\%\times(1-54.5\%))$), and that would be the power generation emissions target set by this study for the scenarios of 2030.

Similarly, according to the "Sustainable Energy Policy Guidelines" published by Executive Yuan of Taiwan in 2008, the national total emissions in 2025 should return to the level of 2000 (i.e., 9.7 ton-CO_{2e}/person). Following the same calculation way of above IPCC emissions standard for 2030, the carbon emissions target for the power sector of 2025 Taiwan is 6.37 ton-CO_{2e}/person ($=9.7-((11.0\times34.3\%)\times(1-11.8\%))$).

Based upon the two “total power generation” criteria for 2025 and 2030—44.5 kWh/person-day and 49.5 kWh/person-day—and the two emissions standards—6.37 ton-CO_{2e}/person set by "Sustainable Energy Policy Guidelines" and 3.28 ton-CO_{2e}/person formulated by

IPCC—this study planned the low-carbon power infrastructure for the future Taiwan accordingly.

Taiwan's Existing Power Structures and Future Development Programs: The BAU Cases

According to the statistics of BOEMOEA (2010a), in 2010 Taiwan, the installed capacity of traditional power plants was 43.05GW, accounting for 92.83% of the total, while the remaining 7.14% was renewables' (3.31GW). Actually, the share of renewable energy power generation was only 3.37%. Meanwhile the total power generation in this country was 247,045GWh. In the energy sector, the carbon dioxide emissions were 167.32Mt, accounting for 65.7% of the all sectors' (BOEMOEA, 2011). Therefore, in Taiwan, energy sector is the main source of GHG emissions, mainly due to its excessive use of fossil fuels—the total installed capacity shares of coal-fired, gas-fired, and oil-fired power plants was 78.35% (MOEMOEA, 2010a). Please refer to TABLE 2 and TABLE 3 for the details.

Furthermore, according to the reference (MOEMOEA, 2010b), in 2025 Taiwan, the planning target of traditional energy generation capacity is 61.71GW (87.4% of the total) with annual growth rate of 2.89%, while that of renewable energy is 8.9GW (12.6% of the total) with annual growth rate of 11.2%. Obviously, Taiwanese Government is conducting its future power infrastructure toward a low-carbon society.

It is worth mentioning that Taiwan currently has three nuclear power plants in operation. Meanwhile, there is a nuclear power plant No. 4 under construction and expected in operation by 2025. The grid connection of this non-carbon power (2.7 GW) could contribute to Taiwan in the realization of a sustainable development. However, due to the occurrence of Fukushima nuclear disaster last year, Taiwanese Government had decided that some ageing nuclear power units would be no longer service-extended. Therefore, the total installed capacities of nuclear facilities in 2025 and 2030 would be reduced. Secondly, based on the annual growth rate of 11.2% between 2010 and 2025, the total installed capacity of renewable energy power plants in 2030 would be 10.77GW, accounting for 14.16% of the total power installed capacity, as shown in TABLE 3. According to the average annual growth rate of 2.8% forecasted by "Long-Term Load Forecast and Development of Power Supply Summary Report" released by BOEMOEA in 2010, the total installed capacities of traditional power plants in 2030 would be 65.31GW, accounting for 85.84% of the total, as shown in TABLE 2.

TABLE 2 THE DEVELOPING STATUS AND PLANNING OF ALL KINDS OF TRADITIONAL POWER PLANTS OF TAIWAN (THE BAU CASES)

Year	2010		2025		2030	
Type of traditional power plant	Capacity (GW)	Share(%)	Capacity(GW)	Share(%)	Capacity(GW)	Share(%)
Coal-fired	18.01	38.84	27.2	40.57	31.3	41.14
Gas-fired	15.72	33.91	23.8	35.49	27.3	35.88
Oil-fired	4.18	9.02	2.87	4.28	2.43	3.19
Nuclear	5.14	11.09	4.28*	6.38	4.28*	5.62
Total	43.05	92.83	58.14	86.71	65.31	85.84

Notes: the ageing nuclear power plants that could be no longer service-extended: No. 2 generator of #1 plant (0.636GW) to be retired in 2019; No.1 generator of #2 plant (0.985GW) to be retired in 2021; No.2 generator of # 2 plant (0.985GW) to be retired in 2023; No.2 generator of # 3 plant (0.951GW) to be retired in 2024.

TABLE 3 THE DEVELOPING STATUS AND PLANNING OF ALL KINDS OF RENEWABLE ENERGY POWER PLANTS OF TAIWAN (THE BAU CASES)

Year	2010		2025		2030	
Type of RE power plant	Capacity (GW)	Share(%)	Capacity(GW)	Share(%)	Capacity(GW)	Share(%)
Hydropower	1.98	4.27	2.50	3.73	2.67	3.51
Wind	0.48	1.04	2.45	3.65	3.11	4.09
PV	0.02	0.04	2.00	2.98	2.66	3.50
Biomass	0.18	0.39	0.30	0.45	0.34	0.45
Waste	0.65	1.40	1.10	1.64	1.25	1.64
Geothermal	-	-	0.15	0.22	0.2	0.26
Fuel cell	-	-	0.20	0.30	0.27	0.35
Marine	-	-	0.20	0.30	0.27	0.35
Total	3.31	7.14	8.9	13.27	10.77	14.16

Analysis of the Characteristics of Various Power Generation Technologies

As shown in TABLE 4, this study had analyzed the characteristics and merits of all kinds of power generation technologies by comparing their performance parameters, such as emissions, availability, generation cost, and net peak output parameter, in order to pursue the optimal design of low-carbon power structure of future Taiwan.

Emissions

To meet the ISO14000 Standard, the "Life Cycle Assessment (LCA) Method", or the so-called "Cradle to Grave Method" has been adopted in this study to calculate the carbon emissions from all power facilities. The calculation considers the GHGs that are emitted from all energy sources throughout the manufacturing chains, including the mining, refining, processing, and transportation of materials. On the other hand, the energy-consuming or power-generating procedures are also considered, including associated operations, maintenance, and down-time.

Although there is no GHG emissions during the generation processes associated with solar PV, ocean energy, hydropower, wind power, and other renewable sources, some GHGs are nevertheless released in the manufacturing of turbines, solar panels and so on. Accordingly, renewables can only be regarded as low-carbon energies, and nuclear power is also generally the case. Traditional coal-fired, gas-fired, oil-fired power plants produce large amounts of greenhouse gases, but with the combination of CCS technology make their emissions significantly reduced.

However, according to the referential literature (Sciencenet, 2012), the CCS technology would decrease the power generation efficiency about 10%-25 and increase the power generation cost approximately 20%-85%. Therefore, when constructing the low-carbon power generation scenarios for future Taiwan, this study assumes that the power generation efficiency of fossil-fueled power plants would decrease 15%, while the corresponding power generation cost would also increase 40% due to the application of CCS technology.

Solar photovoltaics: the manufacture of solar panels requires the extraction of silicon from quartz at high temperature, in which 60% of the energy are consumed in the entire process (POST, 2006). Existing technologies emit around about 0.032 kg-CO_{2e}/kWh of PV power generated, whose value is expected to fall to 0.015 kg-CO_{2e}/kWh in the future (POST, 2006).

Ocean power (wave and tidal): no data on commercialized marine products is yet available; and most carbon dioxide is produced in the steel-making process; today, meanwhile, manufacturing a set of wave energy converter requires 665 tons of steel (with a rated power of 750 kW); the emissions are approximately 0.050 kg-CO_{2e}/kWh; and this value is expected to fall to 0.015 kg-CO_{2e}/kWh (POST 2006).

Hydropower: its carbon emissions are associated with two sources which are storage facilities (such as dams, whose construction involves the emissions of about 0.01 kg-CO_{2e}/kWh) and power facilities (such as turbines, which emit 0.003 kg-CO_{2e}/kWh) (POST, 2006). The emissions associated with the storage facilities are higher, because their construction requires large amounts of concrete and steel. Hydropower is an energy option with low carbon emissions, because the operation of hydropower facilities emits only small amounts of carbon dioxide, but rotted plants in the water release methane.

TABLE 4 THE EMISSIONS, AVAILABILITY, GENERATION COST, AND NET PEAK OUTPUT PARAMETER OF ALL KINDS OF POWER PLANTS (Notes: 1 USD = 30 NTD; 1 GBP = 48 NTD.)

	Emissions (kg-CO_{2e}/kWh)	Availability	Generation cost (NTD/kWh)	Net peak output parameter
Coal-fired	0.9405→0.839	0.78	1.28	0.94
Coal-fired＋CCS	0.125	0.66	1.8	0.94
Gas-fired	0.475→0.389	0.65	1.57	0.98
Gas-fired＋CCS	0.25	0.55	2.2	0.98
Oil-fired	0.778	0.26	1.42	0.90
Nuclear	0.066	0.92	1.7	0.94
Hydropower	0.010-0.013	0.37	2.539	0.70
Wind power	0.09-0.010	0.3	1.3~2.2	0.06
Solar PV	0.032	0.15	4.3	0.20
Biomass power	0.014-0.022	0.57	2.3	0.50
Waste energy	0.341	0.52	2.0	0.80
Geothermal	0.038	0.9	1.8	0.50
Fuel cell	0.664	0.9	2.7	0.85
Marine energy	0.015-0.050	0.3	3.981	0.85

Wind power: about 98% of carbon emissions associated with wind power occur in the construction process, because the manufacture and construction of the tower frame, foundation and blades require steel, cement, glass fiber and resin. During operation, the lubricant and transportation required for maintenance are associated with carbon emissions (POST, 2006). According to the life cycle assessment of wind generation facilities, the carbon emissions associated with onshore wind turbines are around 0.090 kg-CO_{2e}/kWh, while those associated with offshore wind turbines are approximately 0.010 kg-CO_{2e}/kWh (partially owing to their larger foundations) (Benjamin, 2008).

Biomass power: this source is regarded as a "carbon-neutral" source of energy, because the carbon dioxide that is released during the combustion of biomass fuels equals that absorbed by the plant during its growth period. However, if the fertilizers required in the growth period of the plant are considered, then biomass can still only be regarded as low-carbon source of energy. Hence, a preferable source of biomass is an energy crop with a short growth period, such as shrub willow, grass, miscanthus sinensis, straw and wood dust. Since energy crop has a low energy density, the transport of a large amount of biomass is associated with significant carbon dioxide emissions per unit of produced energy. The emissions associated with the generation of power by the combustion of miscanthus sinensis, gasified wood dust, and straw are between 0.014-0.022 kg-CO_{2e}/kWh (Benjamin, 2008). To estimate the emissions associated with biomass in Taiwan, consider miscanthus sinensis as the only biomass crop cultivated in land that is suitable for any biomass crop: the planting area would be around 2,580 km^2 (Chen et al., 2010), and thus it would yield approximately 9.23×10^6 tons/year of wood dust and straw (Chen et al., 2010).

Waste power generation: waste power generation is similar to gas-fired power generation, but the former is different from the latter in that the biomass crops possess the characteristic of "carbon neutral", thus the waste power generation has a higher emissions of 0.341 kg-CO_{2e}/kWh (Dominic, 2006).

Geothermal: geothermal power generation is a renewable energy taking hot spring as heat source to drive power generator, which also does not produce greenhouse gases; and the manufacturing processes of plants and turbine components are the only sources of emissions (only 0.038 kg-CO_{2e}/kWh(Benjamin, 2008)), thus geothermal power can be seen as a low-carbon energy.

Fuel cell: fuel cell uses hydrogen and oxygen to generate electrochemical reaction, the products of which are electricity and water,without the production of carbon dioxide, but currently the sources of hydrogen and oxygen mainly come from the reforming process of fossil fuels (e.g., natural gas and coal) and the electrolysis of water. In terms of life cycle assessment, the fuel cell still cannot be regarded as a low-carbon energy. Currently, the emissions of fuel cell are 0.664 kg-CO_{2e}/kWh (Benjamin, 2008). If the fuel sources for fuel cell are mainly produced from the renewable energy or nuclear power in the future, fuel cell is very likely to be regarded as a low-carbon energy.

Nuclear power generation: the emissions of nuclear power generation are 0.066 kg-CO_{2e}/kWh, 17.4% of which comes from the operation of nuclear power plant, in which there is no need of fuel-burning process. Most of the emissions come from the uranium's mining, enrichment, and production (accounted for 38%), while those of out-of-service are 18.2%, followed by 14% of nuclear waste back-end processing, and 12.4% of plant construction (Benjamin, 2008).

Coal-fired power generation: coal-fired power plant is the largest GHG emissions source among all the power plants today. However, if Integrated Gasification Combined Cycle (IGCC) and Ultra Supercritical Steam Cycle (USCSC) are adopted, the generator efficiencies could respectively increase to 42.7% and 44.5% from 36.8%, and the emissions would be down to 0.839 kg-CO_{2e}/kWh from 0.9405 Kg-CO_{2e}/kWh (Du, 2009).

Coal-fired power + CCS: if cooperated with "pre-combustion" of carbon-capture technology, the emissions of IGCC could reduce to as low as 0.125 kg-CO_{2e}/kWh (POST, 2006). In the IGCC power generation procedure, if undergoing gasification instead of burning coal directly, carbon elements could be separated in advance to form the so-called "synthesis gas"which can be used for power generation or hydrogen production.

Gas-fired power generation: gas-fueled power plant inherently has the lowest carbon dioxide emissions among all the fossil-fueled power plants. Therefore, many countries are developing gas-fired power generation having been regarded as one of the low-

carbon energies nowadays. According to the low-carbon power generation planning of Taipower, if the old gas-fired units are updated, the emissions could be further dropped from 0.475 kg-CO_{2e}/kWh to 0.389 kg-CO_{2e}/kWh (Du, 2009).

Gas-fired power generation + CCS: after the combustion of natural gas, if cooperated with "post-combustion" of the carbon-capture technology, the emissions of above-mentioned gas-fired power generation would be further declined to 0.25 kg-CO_{2e}/kWh (Du, 2009), which is relatively higher than that of coal-fired power + CCS, mainly because the carbon capture efficiency of "post-combustion" is well below that of "pre-combustion".

Oil-fired power plant: emissions from oil-fired power plants are next to those from coal-fired power plants, the value of which is approximately 0.65 kg-CO_{2e}/kWh (Benjamain, 2008). Owing to the volatility of international oil prices, existing oil-fired power plants are slowly being replaced by coal-fired or gas-fired power plants that feature CCS, to reduce financial risk.

Availability

In this study, the availability of a power plant is defined as the ratio between actual and theoretical (maximum) outputs in one year. For example, as listed in TABLE 4, according to the statistics released by BOEMOEA for 2010, the availabilities of coal-fired, gas-fired, oil-fired, and nuclear power plants are separately calculated by division of their total power generations (GWh) by means of the theoretical maximum power generations (i.e., the multiplication of installed capacity (GW) and 8,760 hours). Therefore, the power plant with higher availability means that it has a longer actual generation time in one year. Availability of power plant not only affects the output volume, but also influences the generation cost. In general, the calculation of generation cost of a power plant is to divide the sum of every kind of costs by its total power generation in a specific time period. Therefore, the larger electricity per installed capacity per hour the power plant generates, the lower its generation cost will be.

Power Generation Cost

In general, the electric generation costs of a power plant include two kinds: (1) the internal costs composed of plant's construction, fuel consumption and operational fee; and (2) the external costs resulted from the impacts of power generation on the environment and society. In this paper, since the GHG emissions has already been chosen as a benchmark, only the internal costs are considered herein. As shown in TABLE 4, the major reference is "Anderson, D. (2006), Costs and Finance of Abating Carbon Emissions in the Energy Sector".

Reserve Capacity Ratio

In a year, the demand for electricity is not constant. In Taiwan, for example, the peak electric demand occurs in July (summer). Hence, in planning the national power infrastructure, not only must the annual total electricity produced by the power generation system be consistent with the estimated total annual demand for electricity, but also the highest total generation ("net peak capacity") should be consistent with the estimated generation required at the peak hours ("peak load").

To ensure that an unpredicTABLE increase in demand for electricity during peak hours can be met and to prevent a brownout or blackout which occurs when the "net peak capacity" is lower than "peak load" because of a generator failure, governments require that the "net peak capacity" of the power system must exceed the "peak load" by a percentage that is known as the "reserve capacity ratio". On October 5, 2005, the Executive Yuan of Taiwan set "16%" as the "reserve capacity ratio" for national electrical power systems. The "reserve capacity ratio" is calculated by subtracting "peak load" from "net peak capacity" and dividing the result by "peak load". The contributions of private, public, and cogeneration power plants are all included.

The "reserve capacity ratio" represents the reliability of the power supply, whose value can be increased only by the growth of the installed capacity of the generators, and therefore increasing the costs of power generation. Accordingly, when the program of this study is searching for the optimal combination of classes of power plant in terms of installed capacity, the upper bound on the "reserve capacity ratio" is 16%. If the maximum allowed "reserve capacity ratio" in the power generation scenario were less than 16%, then according to the above rule, the calculation would be based on the alternative maximal value, and the installed capacity of each class of power plant would then be calculated.

Eight Kinds of Least-costing Scenarios of Low-carbon Power Generation

Based upon the contents of aforesaid sections, this study totally planned eight scenarios, in which the least-costing analyses of the low-carbon power infrastructure of Taiwan were conducted. The details are described as the following and shown in TABLE 5. For each scenario, there are 12 kinds of power generation facilities including: coal-fired, gas-fired, oil-fired, nuclear, hydro, wind, solar PV, biomass, wastes energy, geothermal, fuel cells, and ocean energy. Wherein, CCS is only implemented in the coal-fired and gas-fired power plants as CCS has not been commercialized yet, when the scenarios were in design, half of them would exclude the existence of CCS. Under each CCS and non-CCS groups, there are two targeted years—2025 and 2030—respectively corresponding to the domestic emissions standard formulated by "Sustainable Energy Policy Guidelines" and the international emissions standard set by IPCC. Although nuclear power is a low-carbon energy from the viewpoints of engineering and science, amid the international anti-nuclear waves, we had to distinguish the scenarios into another two groups with and without nuclear power. Therefore, under the four designing principles—whether CCS and nuclear power plant exist or not; and are in accordance with two GHG emissions standards respectively regulated by Taiwanese Government and IPCC—there are totally 8 scenarios planned by this study. Please refer to TABLE 5, for the whole picture. Under the satisfaction of three requirements: total power generation threshold, emissions standard, and minimum reserve capacity ratio, this study pursued the most cost-effective power structure for each scenario. In other words, the choice of installed capacity (GW) of each facility has inter-influences on the results of each scenario: the total generation (kWh/person-day), the emissions (ton-CO_{2e}/person-year), the generation cost (NT$/kWh), and the reserve capacity ratio (%). In each scenario, after the cost-optimal installed capacities is attained, their ratios with respective to BAUs are also calculated. These values are the indicators of feasibility. In other words, if the designed installed capacities are closer to (or less than) those of BAUs, it means that the scenario is very feasible.

Comparison and Analysis of Scenarios in the Absence of CCS

Please refer to TABLE 5. First of all, in the case of no CCS, because of high emissions, coal-fired power plant is less considered during the construction of scenario. In the first scenario for the year 2025, compared with BAU, the installed capacity of gas-fired power generation expands 0.85 times, and the expansion of nuclear power is 1.17 times. Under such significant expansion of traditional energies, the resulted generation cost increases moderately (6.78%) by comparison with that of 2010. In this scenario designed for 2025, when there would be no CCS but still with nuclear power, the total generation target and emissions standard could be both met with the total installed capacity of expensive renewables being kept as low as that of 2010.

Similarly for 2025, with the aim of the goals of "Sustainable Energy Policy Guidelines", we considered the more strict condition of no nuclear power in the second scenario. Compared with BAU, the installed capacity of gas-fired expands 0.76 times, while that of renewables is 3.75 times. Therefore, the generation cost significantly increases 18.09%, by comparison with that of 2010.

Regarding the more severe standards of 2030 set by IPCC, in order to meet the demand of greater power supply, in the third scenario, under the existence of nuclear power, by comparison with the BAUs in 2030, the installed capacity of nuclear power significantly expands 5.3 times, and renewables expands 2.9 times, while gas-fired reduces to 0.9 times. Because of the significant expansion of nuclear power and renewables, the average power generation cost significantly increases 25.23% by comparison with that of the year 2010.

In 2030, if there were no nuclear power, the situation would further deteriorate. In fourth scenario, by comparison with BAU, instead of increasing, the installed capacity of gas-fired reduces to 0.62 times, and that of renewables expands 13.4 times. By comparison with 2010, the average generation cost surges 54.5%.

For the above four scenarios without CCS, it can be concluded that under the prerequisite of meeting total power demand, it is almost impossible to meet the international emissions standards, because in the above planning scenarios, compared with BAUs, not only do the renewables have to increase about 3 times to 14 times, but also the nuclear energy must increase at least 1 time, even up to 5 times. Therefore, under the circumstance of no CCS, these planning scenarios are extremely difficult to achieve.

In particular, since the occurrence of Japanese 2011 Fukushima nuclear disaster, Taiwanese nuclear power policy had changed significantlythat nuclear power plant four will be operated as planned, but the ageing power plants will be no longer service-extended in the future, which results in an extreme limitation in terms of nuclear BAU. Indeed, any significant expansion over the BAU will cause that scenario unfeasible. Therefore, if it is assumed that the BAU installed capacity of nuclear power (4.28GW) is smoothly maintained, reducing the installed capacities of gas-fired and coal-fired as low as 0.51 times and 0.29 times those of BAUs, while increasing renewables 2.6 times, then it still has the opportunity to reach the national emissions standard. However, the generation cost would increase 17.78%, by the comparison with 2010. If subjected to such modifications, the feasibility of scenario one would be higher, because the renewables' deployment merely accounted for 9.67% of the estimated total potential. In this alternative scenario, even renewable energy capacity increases 2.6 times than that of BAU, but the average generation cost only increases 17.78%, by comparison with that of 2010. Under the national established policy—pursuing the sustainable goals of energy saving and carbon reduction—such cost increasing scale should be within the government financial tolerance.

Comparison and Analysis of the Scenarios Having CCS

It is assumed that CCS technology could be perfectly applied to fossil-fueled power plants by the year 2025, in scenario five having nuclear power, this research found that when the installed capacities of renewable energy power plants are maintained at current level and the installed capacities of the fossil-fueled power plants (with CCS) are approximately same as BAU, under the satisfaction of total power generation demand, the emissions of scenario five could meet the standard of "Sustainable Energy Policy Guidelines". However, the average generation cost would increase 26.95%, by comparison with that of 2010.

In scenario six planned for the year 2025 when there will be no nuclear power, the installed capacity of renewable energy power plant is maintained same as that of 2010, while that of fossil-fueled power plant is reduced to merely 0.24 times approximately. Under the satisfaction of power generation demand, the emissions of scenario six is far below 2025 domestic standard, while the power generation cost is expensively higher than 32.01%, by comparison with that of 2010, because the generation cost of CCS fossil-fueled power plant is 40% higher than that of traditional fossil-fueled power plant.

Challenging the more severe standards formulated by IPPC for the year 2030, as planned by scenario seven, the installed capacities of CCS fossil-fueled power plants and nuclear power plants are same as those of BAUs, while the installed capacity of renewable energy power plant increases 1.41 times than that of BAU. Under the satisfaction of power generation demand and the international emissions standard, the generation cost of scenario seven increases 32.62%, by comparison with that of 2010.

In scenario eight, namely, there will be no nuclear power plant operational in 2030. The installed capacities of CCS fossil-fueled power plants still are maintained in the BAU levels (i.e., approximately 1.12 times BAU's), while those of renewables are about 1.35 times than BAU's. In the case that the generation cost increases 33.91% over that of 2010, scenario 8 meets the required power generation and emissions standards both of Taiwan and IPCC.

From the analyses of these four scenarios, It can be temporally concluded that with slightly higher emissions, the low cost and high stability make CCS be able to replace the nuclear power as a major low-carbon power generation technology. However, Taiwan lacks of fossil energy, but with abundant renewable energy resources. On the point of view of energy security, Taiwan should rely on renewable energy for the production of electricity.

Therefore, this study additionally includes two scenarios—"Taiwan Power Structure 2010" and "Full Development of Total RE Reserves" in the second and third columns of TABLE 5. Not only do the total generation and reserve capacity ratio of the latter take respectively twice the former, but also the emissions of the latter are 50% far below those of IPCC and are only 20% of the former. However, the price to cover is that the generation cost of total deployment of renewable energy reserves is one times higher than that of current power structure of Taiwan. On this point, this study optimistically believes that in the short or medium term (e.g., before 2025 or 2030), renewables might still be unable to become a mainstream of power generation; but in the long term (such as before 2050), through technologic progresses, like energy storage and smart grid, the shortcomings of renewable power generation would be eventually removed. By then, the

vision of the population of renewable energy over traditional power will be come true.

Conclusion and Discussion

This study first assumed the scenarios without CCS and found that under the installed capacity of coal-fired power plant being 0.22 times than that of BAU, 0.85 times was needed to substantially expand the gas-fired power generation capacity, without increasing the renewable energy capacity, but nuclear capacity 1.17 times is needed to expand, such that above national power infrastructure could reach the emissions reduction target set by "Sustainable Energy Policy Guidelines" and national power supply demand by the year 2025. At that time, the generation cost only increases moderately 6.78%. On the other hand, for the more stringent emission reduction targets set by IPCC and the demand for more power supply by the year 2030, although the gas-fired power generation capacity is reversely reduced about 0.9 times, about 3.9 times significant expansion is needed for renewable energy capacity, while the nuclear power expansion will be about 6.3 times considerablly. This scenario will enable a 25.23% significant increase in the cost of power generation.

Under the circumstance without CCS, confronting the international anti-nuclear voices, if the scenarios of zero nuclear power is supposed, this study found that things would be even worsethat renewable energy would increase about 5 times or even 15 times, making the power costs rise 18.09% or 54.50%, such that the national and international emissions standards as well as national power supply demands could be met. Moreover, although above scenarios could fulfill the emissions targets set by"Sustainable Energy Policy Guidelines"for 2025 and by the IPPC for 2030, the national power supply demands, and the capacity reserve ratio of 16%, large amounts of renewable energy, nuclear energy or gas-fired power plants had to be installed. However, the sharp increase in the power cost was resulted along with the questionable feasibility, because the power generation capacities of planning scenarios are too high over those of BAU. Therefore, this study further assumed the scenarios that CCS could be successfully applied to the coal-fired and gas-fired power plants in the future. Then, regardless of the existence of nuclear power, under the conditions that without substantially expanding renewables and nuclear power, and with the fossil fuel-fired generation capacities close to those of BAU, the objectives of overall power generation and emissions reduction could be fully met, but the power generation cost increases about 34% at most.

Finally, this study concluded that CCS is the effective way for Taiwan to reach a low-carbon power infrastructure, but not the most economical one. Moreover, it cannot be denied that even in the short and medium terms, renewable energy cannot become the mainstream power globally, but in the long term, under the progress and accumulation of science and technology, the shortcomings of renewable (e.g., unstable power supply and high generation costs) will be overcome. Besides, Taiwan is in lack of fossil energy resources, while being abundant with renewable energy resources. On the point of view of secure energy supply, renewable energy development should be considered as a long-term energy policy for this country.

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TABLE 5 SCENARIOS ANALYSES OF LOW-CARBON POWER INFRASTRUCTURE OF TAIWAN

	Scenario	2010	Full development of total RE reserves	No CCS				With CCS			
				2025		2030		2025		2030	
				With nuclear	No nuclear	With nuclear	No nuclear	With nuclear	No nuclear	With nuclear	No nuclear
				Scenario 1: RE(2010), gas-fired(1.85 times), coal-fired(0.22 times), Nuclear(2.17 times)	Scenario 2: RE(4.75 times), gas-fired(1.76 times), coal-fired(0.3 times)	Scenario 3: RE(3.9 times),gas-fired (0.9 times), coal-fired(0), Nuclear(6.3times)	Scenario 4: RE(14.43 times), gas-fired(0.62 times), coal-fired(0.1 times)	Scenario 5: RE(2010), CCS + fossil fueled (1.13 times)	Scenario 6: RE(2010), CCS + fossil fueled(1.24 times)	Scenario 7: RE(1.41 times), CCS + fossil fueled(1.02 times)	Scenario 8: RE(1.35 times), CCS + fossil fueled(1.12 times)
Capacity of power plant（GW）	Coal-fired	18.01	-	6.00	8.00	0.00	3.00	0.00	0.00	0.00	0.00
	Coal-fired＋CCS	-	-	-	-	-	-	41.50	39.00	39.00	41.80
	Gas-fired	15.72	-	44.00	42.00	24.50	17.00	0.00	0.00	0.00	0.00
	Gas-fired＋CCS	-	-	-	-	-	-	16.50	28.00	23.50	26.80
	Oil-fired	4.19	-	2.87	0.00	0.00	0.00	2.87	0.00	0.00	0.00
	Nuclear	5.14	-	9.30	0.00	27.00	0.00	4.28	0.00	4.28	0.00
	Hydropower	1.98	43.49	1.98	11.00	20.00	43.50	1.98	1.98	4.00	3.00
	Wind power	0.48	95.51	0.48	18.00	10.00	56.35	0.48	0.48	4.00	4.00
	Solar PV	0.02	155.06	0.02	8.00	5.00	46.00	0.02	0.02	4.00	3.00
	Biomass power	0.18	3.06	0.18	2.10	3.00	3.00	0.18	0.18	0.90	1.50
	Waste energy	0.65	0.00	1.10	1.10	1.25	1.25	1.10	1.10	1.25	1.25
	Geothermal	0.00	0.71	0.00	0.70	0.70	0.70	0.00	0.00	0.45	0.75
	Fuel cell	0.00	0.00	0.00	0.20	0.20	0.20	0.00	0.00	0.20	0.20
	Marine energy	0.00	14.60	0.00	1.40	2.00	4.60	0.00	0.00	0.60	1.00
Comparison criterion	Total generation (kWh/person-day)	32.77	78.02	46.60	49.07	57.92	60.17	44.56	44.55	49.70	49.64
	Minimum power generation (kWh/person-day)			44.50		49.50		44.50		49.50	
	Average emissions (ton-CO_{2e}/person-year)	6.50	1.47	6.25	6.36	3.25	3.28	2.57	2.78	2.71	2.88
	Emissions standard (ton-CO_{2e}/person-year)			6.37*		3.28**		6.37*		3.28**	
	percentage of total RE reserves	1.10	100.00	1.10	14.52	15.84	58.34	1.10	1.10	4.92	5.16
	Increase percentage of generation costs (%)	0.00	92.35	6.78	18.09	25.23	54.50	26.95	32.01	32.62	33.91
	Reserve capacity ratio (%)	19.35	36.71***	16.12	16.23	16.68	16.22	19.28	23.58	17.01	19.92

Sustainable Energy Policy Guidelines. **: IPCC. ***: The year of 2030